Using a Time of Flight Method for Underwater 3-Dimensional Depth Measurements and Point Cloud Imaging

Chi-Leung Tsui[1], David Schipf[1], Keng-Ren Lin[3], Jonathan Leang[1], Feng-Ju Hsieh[1], Wei-Chih Wang[1,2,4]
[1]Department of Mechanical Engineering
[2]Department of Electrical Engineering
University of Washington
Seattle, Washington
[3]Department of Biomedical Engineering
[4]Medical Device Innovation Center
National Cheng Kung University
Tainan, Taiwan

***Abstract*— Underwater depth measurements and point cloud images can be used for robotic navigation and haptic feedback. Structured Light and Time of Flight (ToF) depth camera systems were tested to demonstrate depth measurements and point cloud imaging underwater. A commercial ToF depth camera was modified to include a movable external light source. Images from depth measurements and constructed point cloud images from underwater tests are shown. A comparison of depth images captured while objects were positioned ~0.10-1.80 m from the camera is presented. Calibration of ToF cameras augmented with movable external light sources for underwater use is discussed.**

Keywords— Depth Camera; Time-of-Flight; Underwater Optics; Haptics; Point Cloud; Kinect

I. INTRODUCTION (*Heading 1*)

Depth cameras have been used for generating 3-dimensional re-constructions of physical space [1] [2] [3]. Point clouds, which are a discrete collection of points that map the surface of a 3-dimensional object [4] have recently been employed to model physical space for machine-human interaction or haptic feedback [2].

Commercially available depth cameras can be used for depth imaging and point cloud construction [2]. The Microsoft Kinect uses a structured light method [5] for depth imaging [1]. Other cameras utilize a time-of-flight (ToF) method for depth imaging [3] [5] [6] [7]. Cameras using the structured light method have been demonstrated to work for point cloud image construction in air [2]. It has not been successfully demonstrated, however, that depth cameras using either the structured light method or the ToF method can be used for point cloud image construction underwater.

There is a need for depth measurements and point cloud imaging underwater. Sea divers conducting high risk tasks can benefit from additional sensory information [11]. If point cloud construction can be achieved underwater, divers could potentially have access to haptic feedback underwater [2]. Autonomous underwater vehicles (AUVs) on mission to map ship hulls can also benefit from a robust depth camera system underwater [9].

The high absorption of electromagnetic waves in water make the use of depth cameras seem inappropriate. At a wavelength of ~800 nm in the near-IR region, however, there is a local minimum in absorption [10] [11], making this region ideal for transmitting depth camera signals. The Microsoft Kinect camera and the Softkinetic DS311 camera, operating with peak wavelengths between 800-830 nm, are then ideal for underwater use. If a position adjustable light source augments a depth camera such as the Kinect or the DS311, the range of optical imaging and haptic feedback underwater from point clouds could theoretically be improved.

This paper describes camera tests for depth imaging and point cloud image construction underwater. Off-the-shelf structured light cameras and time-of-flight (ToF) cameras were deployed underwater to take depth images and to collect point clouds. The time-of-flight camera was modified to include a position adjustable external light source. Underwater and air tests were conducted and resulting depth and point cloud images from measurements were compared.

II. METHODS

A. *Structured Light Depth Camera*

Structured light cameras construct depth images by broadcasting an infrared (IR) light pattern through a grating into an environment. The IR camera captures the reflected pattern and compares it with a pre-calibrated pattern using proprietary computer algorithms.

We first tested the feasibility of operating a structured light depth camera underwater using an off-the-shelf Microsoft Kinect camera. For our underwater measurement, we constructed a waterproof camera housing. The underwater enclosure consisted of a T-shape polyvinyl chloride (PVC) pipe, 1 pipe extender, and a 4 ft long tubing (with a viewport).

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This formed the container of the camera system and conduit for the communication wires (Figure 2a).

The camera was placed inside a large water tank at the Applied Physics Laboratory (APL) with approximate dimensions of 2m diameter and 2m depth. A platform was placed inside of the tank. Objects were manipulated on the platform as the camera captured depth images. Figure 1 shows this setup. The maximum and minimum working distance of the Kinect camera system was tested using the experimental setup shown in Figure 1.

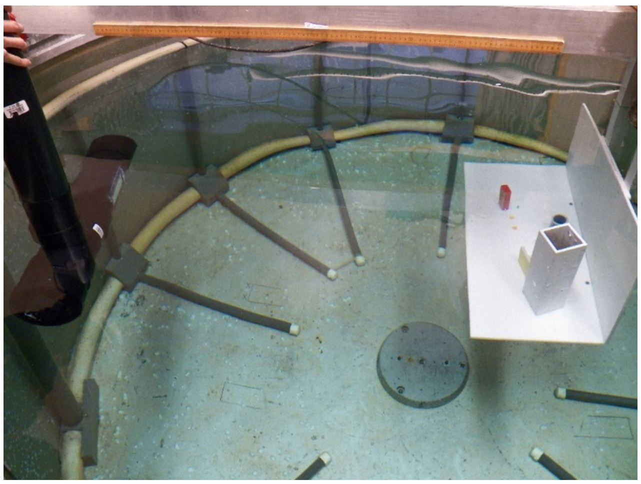

Figure 1. Picture of experiment setup for the camera system inside an underwater enclosure, taking depth images of objects on the submerged platform.

Based on the working principle of the structured light camera, the quality of the image can potentially be improved by: 1) providing a higher intensity light source in the camera system; 2) optimizing the position of the light source or providing multiple light sources at different positions. The improvements should increase the reception of the reflected light by the camera sensor and generate a higher quality depth image.

First, the feasibility of operating a light source from a different position was investigated. We removed the original Kinect light source from its position and attempted to use an external light source, driven by an external power supply. This produced unsatisfactory depth imaging, and so another camera, using a different depth imaging method was then tested.

B. *Time of Flight Depth Camera*

A Softkinetic DS311 ToF camera system was used for testing. The ToF camera also operates in the IR range, which means it should function in a similar fashion to the structured light camera underwater. The DS311 has two modes: a short mode and a long mode. The long mode provides a higher current to the IR LEDs on the camera, giving a higher intensity light source.

The ToF method does not rely on a projected pattern for depth measurement, which makes ToF cameras less vulnerable to environmental conditions influencing depth measurements. Because the ToF method uses a simple phase difference in reflected light, a depth and point cloud image adjustment can be more easily made based on the position of the external light source relative to the camera sensor.

C. *Maximum and Minimum Distance*

The minimum and maximum operating distance of the ToF camera in its stock configuration was tested in the large tank at APL shown in Figure 1. The camera was placed inside an underwater enclosure to protect it from water inside the large tank while still giving it the ability to send and receive IR signals. To accommodate possible reconfiguration of the ToF camera during later tests, two different designs of enclosures were utilized. Pictures of these two configurations are shown in Figure 2.

First, the U-shape enclosure, shown in Figure 2a was used. Then, the glass container, shown in Figure 2b was used to house the camera. The enclosure was placed under a metal beam at the center of the large tank in order to maintain its position and depth. This experimental setup is shown in Figure 3.

The minimum and maximum distance that the camera could capture a depth image was measured by mounting a target 2

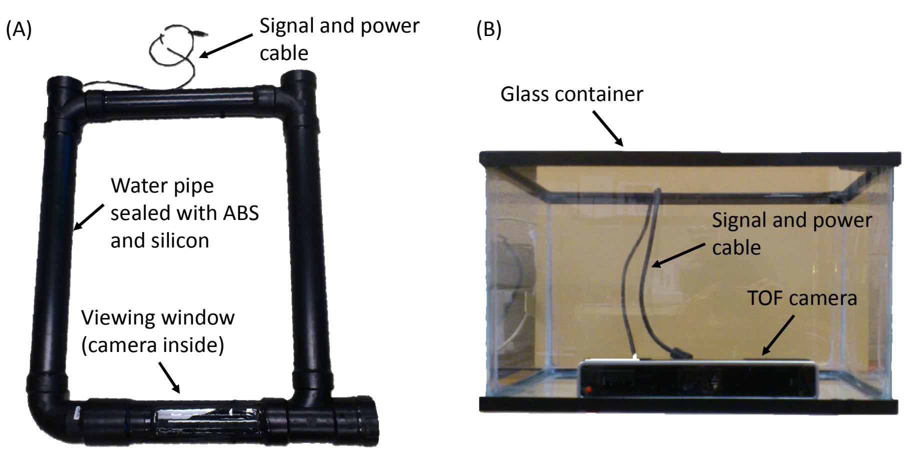

Figure 2. Pictures of the underwater enclosures used for the structured light and TOF Cameras; a) U-Shape tube design made of PVC; b) Glass container design

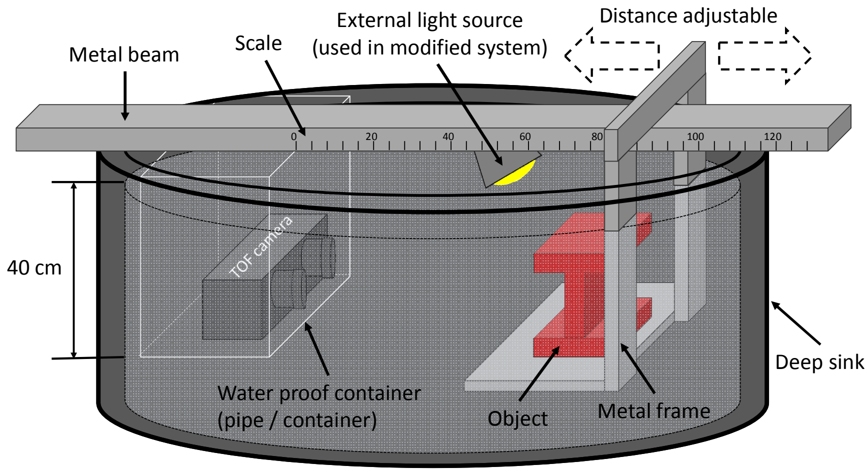

Figure 3. Diagram of experimental setup used in the APL tank for ToF camera underwater depth measurements that included RGB, depth, and point cloud imaging.

cm away from the enclosure that contains the camera along a metal beam at the center of the tank and moving it away from the enclosure. While moving the target, depth measurements and red-green-blue (RGB) images were recorded using DepthViewer from the Softkinetic software development kit (SDK). The working distances were observed by researchers identifying the position of the metal frame relative to the scale on the metal beam. The data was captured every 5 cm.

D. *Point Cloud Construction*

After the maximum and minimum working distance were determined for the stock TOF camera system, point cloud imaging was constructed with measurements taken within the maximum and minimum working distance operation range. The same experimental setup as was used for the distance measurement (Figure 3) was used to construct point cloud images. A custom made platform for holding the test targets was mounted on the metal beam of the APL water tank; the platform allowed the placement of individual objects for obtaining point cloud images at desired distances. The platform was placed at different locations within the camera working distances, and the point cloud image of the target was captured at each location.

E. *External Light Source*

The addition of a position adjustable external light source should in theory extend the working range of the camera system underwater, providing an intensity increase to counter the effect of water absorption. To prove this concept, the Softkinetic DS311 ToF depth camera was connected to an additional array of IR LEDs. The IR LEDs on the camera were made inactive and the IR LEDs on the external light source were activated. The array of active LEDs shown in Figure 4b is herein called the external light source. The external light source was synchronized with the driving signal of the camera light source in order for it to function correctly. Figure 4a shows a diagram of the DS311 ToF camera and Figure 4b shows a picture of the external light source.

The depth camera was placed in the glass container, shown in Figure 2b, and positioned underwater in the APL tank. The external light source was positioned above the water and closer to the target object. This is shown in the top-center portion of Figure 3. The same maximum and minimum working distance tests and point cloud imaging construction was performed using the depth camera and external light source configuration.

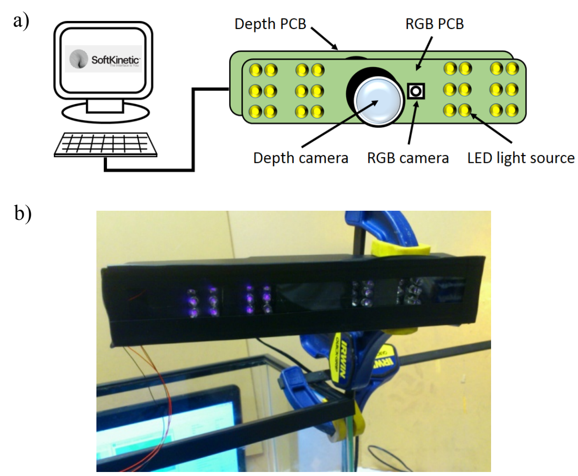

Figure 4. a) Diagram of Softkinetic DS311 ToF camera in stock configuration; b) External light source that was connected to the ToF camera.

III. Results and Discussion

In the following section, the results from the structured light camera system are first discussed. These results informed us of the possibility of using IR depth camera systems for underwater imaging, as well as whether the structured light Kinect camera system can be modified for improved performance in underwater applications. Next, the results from an alternative depth camera system – the ToF Softkinetic DS311 depth camera – are presented. By comparing results from the stock configuration, shown in Figure 4a, with the results from the camera connected to the external light source, shown in Figure 4b, the potential for improved underwater depth imaging by modifying a ToF camera system is demonstrated.

A. Structured Light Depth Camera

The RGB images of objects captured by the structured light Kinect depth camera were compared with depth images. The experimental setup shown in Figure 1 was used. Figure 5a shows objects captured by the RGB camera and figure 5b shows the paired depth image. Figure 5 shows that the structured light camera is able to produce depth images from depth measurements underwater. However, the resulting image is rough when it is compared to the actual object; the edge of the object is noisy and part of the object becomes discontinuous.

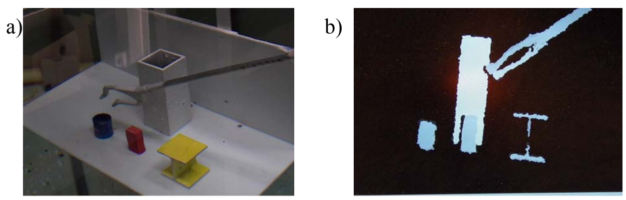

Figure 5. a) Object being manipulated on the platform; b) depth image being captured by the camera in the underwater enclosure.

Modifications were proposed in order to improve the depth imaging produced by the structured light Kinect depth camera. This, however, proved to be difficult due to the proprietary algorithms used by the Kinect. Displacing the light source from its original position caused the depth image to be highly distorted and incomplete. This is shown by the screen capture in Figure 6.

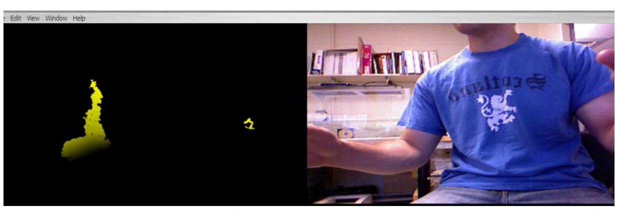

Figure 6. Screen capture of streaming frames from the Kinect while the light source was re-positioned. The left-side image is the depth image and the right-side image is the RGB image.

It was concluded that the system is particular about the position of the light source relative to its sensor, which eliminated the possibility of repositioning the light source and made the task of installing a higher intensity light source difficult. The structured light Kinect depth camera system does not provide flexibility for the light source modifications necessary to ameliorate underwater depth imaging.

B. Time-of-Flight Depth Camera

Minimum and maximum working distances of the ToF Softkinetic DS311 depth camera were determined. Based on our tests with the apparatus shown in Figure 3, The ToF camera produced an operating range of 22cm to 102cm. This range is shown by the images in Figure 8. Similar test performed with the structured light Kinect depth camera system resulted in a range of 64cm to 79cm, which is 19% of the operating range of the Softkinetic DS311 ToF camera system.

The ToF camera was able to capture RGB, depth images, and point cloud images simultaneously on one screen. The point cloud image was constructed using software that utilizes the streaming depth measurements taken by the camera. Screen captures of the images are shown in Figure 7.

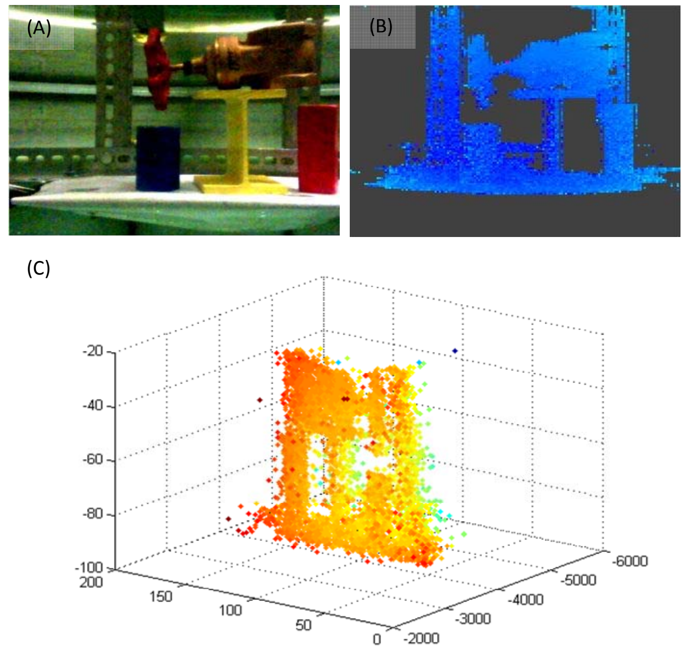

Figure 7. The screen captured a) RGB, b) depth image, and c) point cloud image of target objects placed within the working range of the ToF depth camera on a platform.

C. External Light Source

The ToF camera was modified by attaching the external light source shown in Figure 4b. Tests were conducted in the APL tank according to the experimental setup shown in Figure 3. The images produced by the ToF camera with this modification are compared with images taken by the same camera without the modification in air and water in Figure 8. Figure 8 shows that the external light source was near the object, and so the intensity of the light reflected from the object is greater, producing a more distinguishable image.

D. Point Cloud Data

The point cloud values were compared with measured distances to surfaces on target objects. Figure 9 shows the point cloud values, generated by software running while the depth measurements from the ToF camera were streaming, compared to the pre-measured distances of the objects.

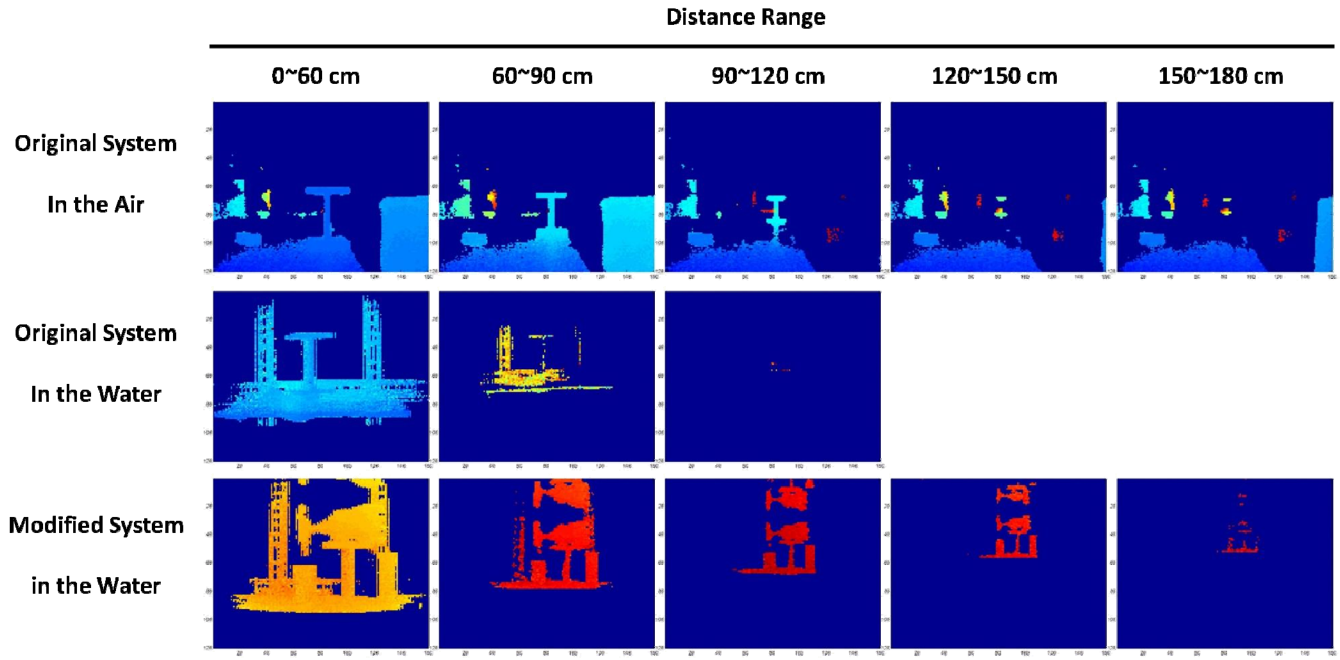

Figure 8. Captured depth image of target over the working distances using different ToF camera configurations.

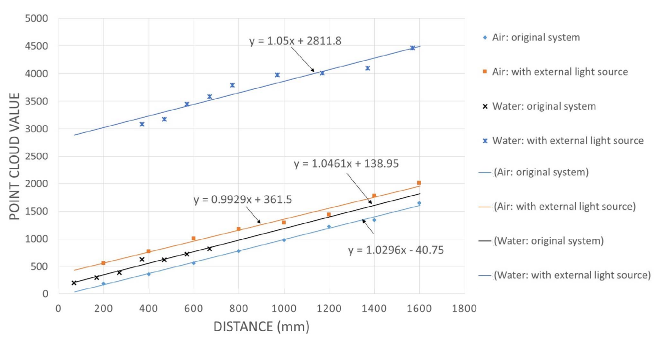

Figure 9. Point cloud value vs actual distance to objects for different ToF camera configurations.

According to Figure 9, the point cloud values and pre-measured distances follow a similar trend. The point cloud values increase linearly while actual distance to the object increases. This is shown by the slope values of the trend lines being 1.05, 0.99, 1.05, and 1.03 for the camera in water with the external light source, the camera in air with the external light source, the stock camera in water and the stock camera in air, respectively. This demonstrates that the point cloud values we captured are numerically meaningful. Additionally, at a distance of 1000mm, the point cloud value was measured to be 1000 while the stock camera configuration was operating in air. This means that the point cloud values were measuring mm units while the camera was operating in conditions that it was designed for.

While the slope of the trend lines of the point cloud values vs. distance is similar for all configurations, the actual values differ slightly and there is an offset in the trend lines. This points to a need for a modified ToF camera system to be calibrated in order to produce point cloud images that accurately re-create 3-dimensional objects. The difference of values between configurations operated in water and air can be explained by the fact that water and air have distinct optical properties (such as index of refraction) that affects how the IR light travels in the individual mediums. The point cloud values for the test in water with the external light source (shown as a dark blue line with asterisk points in Figure 9) is offset from the rest of the point cloud values due to the use of the long mode of the camera for this test. For all of the other measurements shown in Figure 9, the short mode of the camera was used. The long mode provides more intensity from the light source, and so the point cloud values were consistently higher than the point cloud values from the other tests while the camera was in short mode.

The slope of the trend lines plotted in Figure 9 show a correlation between point cloud values and distance to objects that can be used for future point cloud imaging. Given a ToF camera that is augmented with a movable external light source, a calibration method could be deployed in-situ so that point cloud values closely emulate physical distances to objects. This calibration could be as simple as using a multiplicative factor to convert measured point cloud values to mm distances.

IV. Conclusions

The structured light Kinect depth camera and the ToF Softkinetic DS311 depth camera were both demonstrated to capture RGB and depth images underwater. The operational range of the ToF depth camera, operating in its long mode configuration, had a range of 22cm to 102cm, which was 81% greater than the operational range of the Kinect.

The Softkinect DS311 depth camera was augmented by an external light source, which was moved alongside of a target object in order to provide high intensity IR light on the object while the depth camera receiving reflected IR light was static.

This produced more distinguishable images than if the light source was fixed on the camera. The maximum operating distance was increased from 102 cm using the standard configuration to 180 cm using the modified configuration with the external light source. The point cloud values, however, were increased by the increased distance from the light source to the camera. A modified ToF camera will need to include a correction for point cloud values based on relative position between the light source and the camera.

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